

OPTIMAL PESTICIDE USAGE WITH RESISTANCE AND ENDOGENOUS TECHNOLOGICAL CHANGE

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by

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Introduction

Resistance is an important issue in the use of agricultural pesticides: according to the National Audubon Society, in 1993, 504 insect species were known to be resistant to at least one formulation of pesticide, while one hundred and fifty fungi and other plant pathogens had developed resistance to fungicides (Cate and Tinkle, 1994). As for weeds, 212 herbicide resistant weed biotypes were reported to be in existence in 1998 (Heap, 1998).

An important recent event that has brought the issue of resistance management to the forefront of the policy debate has been the successful introduction of plants genetically engineered to produce pesticides. The first generation of these products uses toxins produced by a bacterium, *Bacillus thuringiensis* (*Bt*). The rapid expansion of these products poses important policy questions on how to utilize these new resources so that resistance buildup is limited. For instance, according to the Third Biennial National Organic Farmers' Survey conducted by the Organic Farming Research Foundation (OFRF, 1999), *Bt* sprays are the most important external input used by organic farmers for pest management. Moreover, *Bt* sprays are used on over half of the US production of crops such as celery, cabbage and fresh tomatoes (USDA, 1999). There is a concern that the heavy use of *Bt* toxins produced by the plant pesticides will cause resistance to develop, thereby depriving farmers of the possibility to use *Bt* sprays (EPA, 1998a). In order to preserve susceptibility, the EPA has mandated the institution of resistance management plans.

The rationale for such initiatives is that the use of pesticides poses an impure public goods problem: utilization jointly generates a (positive) private characteristic,

which depends on the individual farmer's use of the chemical, and a (negative) public characteristic, that is, the reduction in susceptibility. Susceptibility tends to have a common property nature because the effect of each farmer's use is minimal, therefore farmers ignore the impact that their actions have on resistance. Moreover, pests are mobile, so first-best behavior today does not guarantee successful outcomes of the pesticide application in the future. Though susceptibility is a scarce resource, resistance management plans that slow down resistance development are costly, and they can only reduce the impact of pesticide usage on resistance development and not eliminate it. The value of resistance management must be weighted against the costs of developing alternative technologies: if new active ingredients are regularly discovered and made available for commercialization, it might be socially optimal to devote more resources to research and development activities and let susceptibility to the existing active ingredients be mined rapidly. Thus, society faces two simultaneous decisions in the use of pesticides: how to allocate the existing stock of biological capital - susceptibility¹ – among farmers and through time, and how many resources to invest in the discovery of new agents effective against the pest.

The object of this paper is to explicitly identify the public nature characteristics of susceptibility in a dynamic setting and to characterize the optimal intertemporal usage problem from a social planner perspective. This allows us to discuss the two concomitant decisions outlined above. First, we derive the optimal level of pesticide use, that is, we explicitly characterize the trade-off between present and future use of a pesticide, as research on new compounds goes on. Secondly, we characterize the optimal amount of

¹ See Hueth and Regev (1974) for a discussion of the concept of biological capital.

resources to allocate to the development of new chemicals. The decision of how many resources to devote to research efforts aimed at discovering new chemical compounds will depend on these activities' relative costs and benefits. These costs and benefits will in turn be a function of both stock and flow variables, such as the production costs of the chemicals, the level of susceptibility of the existing resource and the overall amount of effort already spent on research.

We will focus here on research towards the discovery of novel technologies. Historically, novel pesticides have tended to combine lower toxicity for humans and alternative modes of actions, and have ranged from chemical modifiers of development and behavior (pheromones, growth regulators) to artificial analogues of natural elements, such as the chloronicotinyls (from nicotine) to insect-tolerant plants and genetically modified crops, like the *Bacillus thuringiensis* plant-pesticides (Pedigo, 1999).

The seminal paper on resistance development, by Hueth and Regev (1974), focuses on resistance development within one season. Taylor and Hadley (1975) develop an explicit genetic model of resistance inheritance, while later works, such as Regev *et al.* (1983), Lazarus and Dixon (1984), and Clark and Carlson (1990) analyze the possible problems deriving from the common property nature of pests. While the pesticide literature has taken into account the effects of the externalities created by the use of pesticides, it has not integrated these considerations with the possibility of backstops. On the other hand, an extensive amount of economics literature, spurred by the energy crisis of the early '70s, has analyzed the issues related to the use of a nonrenewable resource when the discovery of backstops is uncertain. Dasgupta and Heal's seminal paper (1974) studies the problem of optimal use when there is uncertainty on the date of discovery of

the new, non-exhaustible technology (and not on its characteristics). The probability of the discovery date is exogenous, and there are no investment efforts. The authors prove that in certain circumstances the uncertainty is formally equivalent to an increase in the discount rate. Kamien and Schwartz (1978) and Dasgupta, Heal and Majumdar (1977) extend the model to endogenize the level of investment which accelerates the time of discovery of the new technology. Davison uses essentially the same framework for the case in which the probability of discovering a backstop is a function of the flow of R&D and not its stock. The model presented here will integrate common property considerations and the existence of technological progress in the determination of optimal use.

A caveat is in order. Susceptibility could be modeled both as a non-renewable and a renewable resource. The choice impinges on the relative fitness of the resistant individuals compared to the susceptible ones. Should there be a fitness cost for the resistant organisms, they would tend to disappear once the usage of the chemical selecting for them had been stopped. Since the entomological literature reports various instances of lack of fitness costs², and the economic literature mentioned above assumes no fitness cost, we will model susceptibility as a non-renewable resource.

In the next pages, we will develop a profit maximization model with heterogeneous farmers and we will apply some of the approaches developed in the energy literature to determine the optimal time path for the depletion of susceptibility to an existing pesticide and to discuss the characteristics of the discovery process. We will assume that technological change is endogenous and analyze the dynamics of research in backstop

² See for instance Andrews and Morrison (1997) Croft and Whalon (1983), Penrose (1990), and Romero and Sutton (1998).

technologies in an uncertain world.

The basic framework

We assume that farmers are risk neutral profit maximizers who face a dichotomous choice in the use of the pesticide. The rationale is that we are dealing with a pesticide such as *Bt* corn, where there is no dose issue. Alternatively, this analysis can be applied to farmers that follow the recommended dose instruction to the letter. As discussed in more detail below, farmers cannot use their past infestation as a predictor for the future and the development of resistance has a public good nature, thus each individual takes the existing stock of susceptibility E as given and his/her contribution to resistance development as negligible. We will assume that farmers only choose whether to apply pesticide or not. The motivation for this assumption is that farmers decide whether to apply the pesticide after they have determined the use of other inputs, such as the type of tillage and the amount of fertilizer³. This characterization allows us to focus on the optimal use of the pesticide and not on input substitution.

We define treatment for farmer i as $e_i = 1$ and no treatment as $e_i = 0$, with p as the price of the pesticide. We assume that the marginal cost of production of the pesticide, χ , is constant, and the chemical industry is perfectly competitive⁴, so that $p = \chi$ ⁵. Without loss of generality, we normalize yield without pest damage to 1, and crop price to 1. We parameterize the level of pest infestation each farmer i suffers from as $\theta_i \in [\underline{\theta}, \bar{\theta}]$.

³ Alternatively, we could assume input separability.

⁴ The chemical industry is also myopic in its behavior towards resistance, since E is a public good.

⁵ This is a simplification in the case of patented pesticides, but it reflects reality for older chemicals.

Specifically, $\theta_i \in \square, \theta_i \in [0, n]^6$, so that at $\theta_i=0$, the farmer suffers no damage, and at n he suffers the biggest damage among the farmers' population, which has size $n+1$. In particular, to calculate explicit results, we will assume that the severity of infestation equals $\frac{\theta_i^2}{n^2}$, so that the returns from not using the pesticide are $1 - \frac{\theta_i^2}{n^2}$. We also assume that, in each period of time, the infestation level θ_i is independent of the θ_i of the previous period. This indicates that the pest population is highly mobile.

Therefore, if the farmer chooses $e_i = 0$, his profit will be given by:

$$\pi_i(\theta_i, e_i = 0) = \left(1 - \frac{\theta_i^2}{n^2}\right) \quad (1)$$

If farmers use the pesticide, their profit is no longer a function of the severity of the infestation, but only of the level of susceptibility to the pesticide of the pest population. This parameterization is equivalent to the assumption made by Hueth and Regev that the pesticide action is not density dependent. The higher the level of susceptibility, the higher the profit. We normalize the stock of susceptibility E to the $[0, 2^n - 1]$ interval, and assume that the efficacy of the pesticide is parameterized by $\frac{\ln(1 + E)}{n \ln(2)}$. Therefore:

⁶ It would be possible to choose a more complex distribution that puts some mass at θ_i . This would not change the quality of the results.

$$\pi_i(\theta_i, e_i = 1) = \frac{\ln(1 + E)}{n \ln(2)} - p. \quad (2)$$

When the efficacy of the pesticide is at its maximum, that is, when the pests are all susceptible, and $E = 1$, then $\pi_i(\theta_i, e_i = 1) = 1 - p$. As E declines, so do the returns for the farmers using the pesticide, thus, while overuse of the pesticide persists, the absolute level of usage decreases with time as efficacy decreases. The farmer's maximization in each time period then consists of a discrete choice problem:

$$\pi_i(\theta_i, e_i = 0) = \left(1 - \frac{\theta_i^2}{n^2}\right) \text{ vs. } \pi_i(\theta_i, e_i = 1) = \frac{\ln(1 + E)}{n \ln(2)} - p, \text{ and}$$

$$\begin{aligned} \text{if } \frac{\ln(1 + E)}{n \ln(2)} - p &\geq \left(1 - \frac{\theta_i^2}{n^2}\right) \Rightarrow e_i = 1, \text{ and} \\ \text{if } \frac{\ln(1 + E)}{n \ln(2)} - p &< \left(1 - \frac{\theta_i^2}{n^2}\right) \Rightarrow e_i = 0. \end{aligned}$$

Therefore, for farmers with a serious infestation, for whom $\frac{\theta_i^2}{n} \rightarrow 1$, using the pesticide will be worthwhile even if the level of susceptibility is low. More specifically, for the farmer with the highest pest population, for whom $\frac{\theta_i^2}{n} = 1$, it will always be worthwhile to treat his fields as long as $\frac{\ln(1 + E)}{n \ln(2)} > p$. Increases in the pesticide price p , will decrease the number of farmers treating their crops, since if $p_0 > p_1$:

$$\theta_i^0 = n \sqrt{1 + p_0 - \frac{\ln(1+E)}{n \ln(2)}}, \text{ and}$$

$$\theta_i^1 = n \sqrt{1 + p_1 - \frac{\ln(1+E)}{n \ln(2)}}, \text{ so}$$

$$\theta_i^0 - \theta_i^1 = n \sqrt{1 + p_0 - \frac{\ln(1+E)}{n \ln(2)}} - n \sqrt{1 + p_1 - \frac{\ln(1+E)}{n \ln(2)}} > 0.$$

The stock of susceptibility to pesticides used until time t , denoted by E , is such that its behavior through time can be described by the following equation of motion:

$$\dot{E} = -\omega \sum_{i=0}^{n+1} e_i. \quad (3)$$

Where ω is the marginal impact of individual usage on resistance development. This characterization of the problem's dynamics indicates that the increase in resistance taking place in each period affects only the future effectiveness of the pesticide. This lag is due to the fact that resistance takes some time to spread. We can then see how farmers overuse the pesticide, as they do not take into account the impact of their use on resistance build-up. In the socially optimal case, the comparison is between $\left(1 - \frac{\theta_i^2}{n^2}\right)$

and $\frac{\ln(1+E)}{n \ln(2)} - p - \mu\omega$, where μ represents the shadow price of susceptibility. We will

discuss the social optimum more explicitly next.

First scenario: no substitutes to the pesticide

We start by discussing the simplest case. In this scenario, there are no alternatives to the pesticide, and resistance management is the only activity that can slow down the mining of susceptibility. This is not necessarily a realistic scenario, since it assumes that no technological change is possible, but it is useful in setting the stage of the problem.

The social planner seeks to maximize⁷:

$$\text{Max}_{\pi_i \forall i} \int_0^{\infty} \left[\sum_{i=0}^{\gamma} \pi_i (\text{no pesticide use}) + \sum_{i=\gamma+1}^{n+1} \pi_i (\text{pesticide use}) \right] e^{-rt},$$

$$\text{s.t. } \dot{E} = -\omega(n - \gamma).$$

Assuming that n is large, so that the proportion of farmers not using the pesticide, γ/n , can be treated as a continuous variable, and remembering that

$$\sum_{i=1}^K i^2 = \frac{1}{6} K(K+1)(2K+1),$$

we can reformulate the problem as:

$$\text{Max}_{\frac{\gamma}{n}} \sum_{i=0}^{\gamma} \pi_i (\text{no pesticide use}) + \sum_{i=\gamma+1}^{n+1} \pi_i (\text{pesticide use}).$$

We can rearrange the maximand:

⁷ Note that this maximization indicates the lack of credit markets for both the government and individual agents.

$$\sum_{i=0}^{\gamma} \left(1 - \frac{\theta^2}{n^2} \right) + \sum_{i=\gamma+1}^{n+1} \left(\frac{\ln(1+E)}{n \ln(2)} - p \right) =$$

$$(\gamma+1) - \frac{\gamma(\gamma+1)(2\gamma+1)}{6n^2} + \frac{\ln(1+E)}{n \ln(2)} (n-\gamma) - (n-\gamma)p.$$

The present value Hamiltonian is then:

$$H = \left[(\gamma+1) - \frac{\gamma(\gamma+1)(2\gamma+1)}{6n^2} + \frac{\ln(1+E)}{n \ln(2)} (n-\gamma) - (n-\gamma)p \right] e^{-rt} - \mu \omega (n-\gamma).$$

We rewrite the Hamiltonian in terms of the proportion of farmers not using the pesticide:

$$H = \int_0^{\infty} \left[\left(\frac{\gamma}{n} n + 1 \right) - \frac{\left(\frac{\gamma}{n} n \right) \left(\frac{\gamma}{n} n + 1 \right) \left(2 \frac{\gamma}{n} n + 1 \right)}{6n^2} + \left(n - \frac{\gamma}{n} n \right) \frac{\ln(1+E)}{n \ln(2)} - p \left(n - \frac{\gamma}{n} n \right) \right] e^{-rt}$$

$$- \mu \omega \left(n - \frac{\gamma}{n} n \right).$$

We can simplify this to:

$$H = \int_0^{\infty} \left[\left(\frac{\gamma}{n} n + 1 \right) - \left[\left(\frac{\gamma}{n} \right)^3 \frac{n}{3} + \left(\frac{\gamma}{n} \right)^2 \frac{1}{2} + \left(\frac{\gamma}{n} \right) \frac{1}{6n} \right] \right] e^{-rt} - \mu n \omega \left(1 - \frac{\gamma}{n} \right).$$

$$+ \left(1 - \frac{\gamma}{n} \right) \frac{\ln(1+E)}{\ln(2)} - p n \left(1 - \frac{\gamma}{n} \right) \quad (4)$$

The first order conditions are:

$$0 = \frac{\partial H}{\partial \gamma/n} = \left[n - \left[\left(\frac{\gamma}{n} \right)^2 n + \left(\frac{\gamma}{n} \right) + \frac{1}{6n} \right] - \frac{\ln(1+E)}{\ln(2)} + np \right] e^{-rt} + \mu n \omega, \quad (5)$$

$$\mu = \frac{1}{\omega} \left[-1 + \left[\left(\frac{\gamma}{n} \right)^2 n + \left(\frac{\gamma}{n} \right) + \frac{1}{6n} \right] \frac{1}{n} + \frac{\ln(1+E)}{n \ln(2)} - p \right] e^{-rt}, \quad (6)$$

$$\dot{\mu} = -\frac{\partial H}{\partial E} = -\left(1 - \frac{\gamma}{n} \right) \frac{1}{(1+E) \ln(2)} e^{-rt}. \quad (7)$$

The transversality condition for E is: $E \geq 0$, and $\lim_{t \rightarrow \infty} E(t)\mu(t) = 0$. As $E \rightarrow 0$,

$\gamma \rightarrow 1$. If $\chi > 0$, the resource will not be extracted completely.

Equation (5) characterizes the optimal number of farms treating for infestations, at which the marginal benefits of using the pesticide,

$$\left[\frac{\ln(1+E)}{n \ln(2)} - 1 + \left[\left(\frac{\gamma}{n} \right)^2 + \left(\frac{\gamma}{n^2} \right) + \frac{1}{6n^2} \right] \right] e^{-rt}, \text{ equal the marginal costs: } pe^{-rt} + \mu \omega.$$

Equation (7) illustrates how the shadow value of susceptibility decreases over time because the resource becomes less and less effective.

PROPOSITION 1 – The proportion of farmers not using the pesticide increases over time if the discount rate is positive.

PROOF:

We take the derivative of (6) with respect to time, and equate it to (7):

$$\begin{aligned}\dot{\mu} = & \frac{1}{\omega} \left\{ \left[2 \left(\frac{\gamma}{n} \right)_{n+1} \right] \frac{1}{n} \left(\frac{\dot{\gamma}}{n} \right) - \frac{\omega(n-\gamma)}{n(1+E)\ln(2)} \right\} e^{-rt} \\ & - r \frac{1}{\omega} \left\{ -1 + \left[\left(\frac{\gamma}{n} \right)^2 n + \left(\frac{\gamma}{n} \right) + \frac{1}{6n} \right] \frac{1}{n} + \frac{\ln(1+E)}{n\ln(2)} - p \right\} e^{-rt},\end{aligned}$$

and since $\dot{\mu} = -\frac{\partial H}{\partial E} = -\left(1 - \frac{\gamma}{n}\right) \frac{1}{(1+E)\ln(2)} e^{-rt}$, we can write:

$$\left[2 \left(\frac{\gamma}{n} \right)_{n+1} \right] \frac{1}{n} \left(\frac{\dot{\gamma}}{n} \right) = r \left\{ -1 + \left[\left(\frac{\gamma}{n} \right)^2 n + \left(\frac{\gamma}{n} \right) + \frac{1}{6n} \right] \frac{1}{n} + \frac{\ln(1+E)}{n\ln(2)} - p \right\}. \quad (8)$$

This result implies that, if the discount rate is zero, the optimal policy is to have a constant percentage of farmers not using the pesticide. The level of social welfare will however decrease over time as the efficacy of the pesticide declines. If, on the other hand, $r > 0$, $\left(\frac{\dot{\gamma}}{n} \right) \geq 0$, as the term in brackets is positive. This results illustrates that in the first best, resistance management plans will be used to slow down the mining of susceptibility. We now analyze the more realistic case of an uncertain backstop.

Third scenario: uncertain non-exhaustible substitutes

In this scenario, the discovery a backstop technology is not certain, and the probability of developing a new (non-exhaustible) technology is endogenous, depending positively on the cumulative amount of R&D effort. We suppose that the new technology is a real breakthrough, so that it renders the stock of susceptibility remaining at the time of the discovery worthless. A good example would be the introduction of

pest-tolerant plants. In this case, no resistance develops to the new technology, so that we can consider the innovation renewable. Define T as the time at which the new technology becomes available, and W as the maximum social welfare possible after the new technology is discovered:

$$W = \max_T \int \left(\sum_{i=1}^n U^i \right) e^{-r(t-T)} dt. \quad (9)$$

As we said above, the probability of discovering a backstop technology is endogenous, and depends positively on the cumulative amount of R&D effort. Define the level of R&D in each time period as I , and the cumulative level of R&D, or stock of knowledge capital, as K . We will assume that the dynamic relationship between stock and flow of knowledge has the same structure as in the previous scenario:

$$\dot{K} = g(I), \quad (10)$$

s.t. $K(0) = 0, f(0) = 0, f' > 0$, and $f'' < 0$.

We define the probability of discovering the backstop as $\phi(K)$. $\phi(K)$ is such that $\phi(0) = 0$, $\phi'(0) = 0$, $\phi' \geq 0$, and $\lim_{z \rightarrow \infty} \phi(z) = 1$. This is the same structure of the R&D function specified in Kamien and Schwartz (1978). The probability of discovering the new technology in the interval dt equals $d\phi(K(t)) = \phi'(K(t)) \dot{K}(t) dt = \phi'(K(t)) f(I) dt$.

In their seminal 1974 paper, Dasgupta and Heal prove that if $W_E = 0$, as we have assumed here, a certain kind of certainty equivalence results, so that the maximization can be rewritten as:

$$\text{Max}_{\frac{\gamma}{n}, I} \int_0^{\infty} \left\{ \left[\left(\frac{\gamma}{n} n + 1 \right) - \left[\left(\frac{\gamma}{n} \right)^3 \frac{n}{3} + \left(\frac{\gamma}{n} \right)^2 \frac{1}{2} + \left(\frac{\gamma}{n} \right) \frac{1}{6n} \right] \right] \right. \\ \left. + \frac{\ln(1+E)}{\ln(2)} \left(1 - \frac{\gamma}{n} \right) \right. \\ \left. + (n+1)(m-x) - p \left(n - \frac{\gamma}{n} n \right) - g(I) \right\} (1 - \phi(K)) + \phi'(K) f(I) W e^{-rt} dt,$$

s.t.

$$\dot{E} = -\omega \left(n - \frac{\gamma}{n} n \right) \quad (\text{multiplier } \mu), \text{ and}$$

$$\dot{K} = f(I) \quad (\text{multiplier } \eta).$$

The optimal control problem has two control variables: $\frac{\gamma}{n}$ and I , and two state variables, E and K . In general terms, utilization of the pesticide shall cease in finite time at, say, T^* since the susceptibility that makes it effective is nonrenewable. The presence of uncertainty might modify the optimal T^* , but, since the discovery of a backstop in the period $[0, T^*]$ cannot be guaranteed, it might be the case that the susceptibility of the pesticide is exhausted before an alternative technology is invented. We define the social welfare function before the introduction of the backstop as:

$$\Gamma\left(\frac{\gamma}{n}, I, E\right) = \left(\frac{\gamma}{n}n + 1\right) - \left[\left(\frac{\gamma}{n}\right)^3 \frac{n}{3} + \left(\frac{\gamma}{n}\right)^2 \frac{1}{2} + \left(\frac{\gamma}{n}\right) \frac{1}{6n}\right] + \frac{\ln(1+E)}{\ln(2)} \left(1 - \frac{\gamma}{n}\right) + (n+1)(m-x) - p\left(n - \frac{\gamma}{n}n\right) - g(I).$$

Then the Hamiltonian is:

$$H = \left\{ \Gamma\left(\frac{\gamma}{n}, I, E\right) (1 - \phi(K)) + \phi'(K) f(I) W \right\} e^{-rt} + \mu - \omega \left(n - \frac{\gamma}{n}n\right) + \eta f(I).$$

The first order conditions are:

$$0 = \frac{\partial H}{\partial \gamma/n} = \left[n - \left[\left(\frac{\gamma}{n}\right)^2 n + \left(\frac{\gamma}{n}\right) + \frac{1}{6n} \right] - \frac{\ln(1+E)}{\ln(2)} + np \right] (1 - \phi(K)) e^{-rt} + \mu n \omega, \quad (11)$$

$$0 \geq \frac{\partial H}{\partial I} = [-g'(I)] (1 - \phi(K)) e^{-rt} + \phi'(K) f'(I) W e^{-rt} + \eta f'(I), \quad (12)$$

$$\eta = \frac{g'(I)}{f'(I)} (1 - \phi(K)) e^{-rt} - \phi'(K) W e^{-rt}, \quad (13)$$

$$\dot{\eta} = -\frac{\partial H}{\partial K} = \phi'(K) \Gamma\left(\frac{\gamma}{n}, I, E\right) e^{-rt} - \phi''(K) f(I) e^{-rt} W, \quad (14)$$

$$\dot{\mu} = -\frac{\partial H}{\partial E} = -\left(1 - \frac{\gamma}{n}\right) \frac{1}{(1+E)\ln(2)} (1 - \phi(K)) e^{-rt}, \quad (15)$$

$$\mu = \frac{1}{\omega} \left\{ -1 + \left[\left(\frac{\gamma}{n}\right)^2 n + \left(\frac{\gamma}{n}\right) + \frac{1}{6n} \right] \frac{1}{n} + \frac{\ln(1+E)}{n\ln(2)} - p \right\} (1 - \phi(K)) e^{-rt}. \quad (16)$$

Equation (11) is the equivalent to equation (5) in the previous scenario: at the optimum, the marginal benefits of using the pesticide,

$$\left[\frac{\ln(1+E)}{n \ln(2)} - 1 + \left[\left(\frac{\gamma}{n} \right)^2 + \left(\frac{\gamma}{n^2} \right) + \frac{1}{6n^2} \right] \right] (1 - \phi(K)) e^{-rt},$$

are equal to the marginal costs:

$\mu\omega + p(1 - \phi(K))e^{-rt}$. The equalization of marginal costs and benefits determines the optimum level of investment as well, once $I > 0$, as shown in equation (13). The cost of investment is represented by $[g'(I)](1 - \phi(K))e^{-rt}$, and the benefits by $\phi'(K)f'(I)We^{-rt} + \eta f'(I)$.

PROPOSITION 8 – The proportion of farmers not using the pesticide increases through time.

PROOF:

We take the derivative of (16) with respect to time, and equate it to (15):

$$\begin{aligned} \dot{\mu} &= \frac{1}{\omega} \left\{ \left[2 \left(\frac{\gamma}{n} \right) n + 1 \right] \frac{1}{n} \left(\frac{\dot{\gamma}}{n} \right) - \frac{\omega(n - \gamma)}{n(1 + E) \ln(2)} \right\} (1 - \phi(K)) e^{-rt} \\ &\quad - r \frac{1}{\omega} \left\{ -1 + \left[\left(\frac{\gamma}{n} \right)^2 n + \left(\frac{\gamma}{n} \right) + \frac{1}{6n} \right] \frac{1}{n} + \frac{\ln(1 + E)}{n \ln(2)} - p \right\} (1 - \phi(K)) e^{-rt} \\ &\quad - \frac{1}{\omega} \left\{ -1 + \left[\left(\frac{\gamma}{n} \right)^2 n + \left(\frac{\gamma}{n} \right) + \frac{1}{6n} \right] \frac{1}{n} + \frac{\ln(1 + E)}{n \ln(2)} - p \right\} \phi'(K) f'(I) e^{-rt}, \text{ and} \\ \dot{\mu} &= -\frac{\partial H}{\partial E} = -\frac{(n - \gamma)}{n(1 + E) \ln(2)} (1 - \phi(K)) e^{-rt}, \text{ therefore} \end{aligned}$$

$$\left[2\left(\frac{\gamma}{n}\right)^{n+1}\right]\frac{1}{n}\left(\frac{\gamma}{n}\right)^{\cdot}=r\left\{-1+\left[\left(\frac{\gamma}{n}\right)^2n+\left(\frac{\gamma}{n}\right)+\frac{1}{6n}\right]\frac{1}{n}+\frac{\ln(1+E)}{n\ln(2)}-p\right\} \\ +\left\{-1+\left[\left(\frac{\gamma}{n}\right)^2n+\left(\frac{\gamma}{n}\right)+\frac{1}{6n}\right]\frac{1}{n}+\frac{\ln(1+E)}{n\ln(2)}-p\right\}\frac{\phi'(K)f(I)}{(1-\phi(K))} \quad (17)$$

Note that the first term is identical to the expression on the RHS of equations (8)

in the certainty case. In this case, however, if $r = 0$, we have that $\left(\frac{\gamma}{n}\right)^{\cdot} > 0$, since we can

rewrite (17) as $\left(\frac{\gamma}{n}\right)^{\cdot} = \omega \frac{\mu}{\left[2\left(\frac{\gamma}{n}\right)^{n+1}\right]\frac{1}{n}} \frac{\phi'(K)f(I)}{(1-\phi(K))^2} e^{rt}$, and μ , the shadow value of

susceptibility, is positive. Also, note how the time path of the optimal fraction of farmers that treat for pest infestation depends on the structure of the uncertainty.

PROPOSITION 9 – The level of investment increases through time. The increase is higher if the discount rate is positive.

PROOF:

At $t = 0$, $K = 0$. Therefore, either $I(0) = 0$ and $0 > -g'(0) + \eta(0)f'(0)$, or $I(0) > 0$ and $0 = -g'(0) + \eta(0)f'(0)$. If $I(0) = 0$, then at $t > 0$, $\dot{\eta} = 0$ and $\eta(t) = \eta(0)e^{rt}$. Therefore, as time passes and $I(0) = 0$, $0 > -g'(0) + \eta(0)e^{rt}f'(0)$ till η increases enough to have $0 = -g'(0) + \eta(0)e^{rt}f'(0)$. If $I > 0$, we take the derivative of (13) with respect to time, and equate it to (14):

$$\begin{aligned}
\dot{\eta} &= \left[\frac{g''(I)f'(I) - g'(I)f''(I)}{f'(I)^2} \dot{I} (1 - \phi(K)) - \frac{g'(I)}{f'(I)} \phi'(K)f(I) - \phi''(K)f(I)W \right] e^{-rt} \\
&\quad - r \left[\frac{g'(I)}{f'(I)} (1 - \phi(K)) - \phi'(K)W \right] e^{-rt}, \text{ and} \\
\dot{\eta} &= -\frac{\partial H}{\partial K} = \phi'(K)\Gamma\left(\frac{\gamma}{n}, I, E\right)e^{-rt} - \phi''(K)f(I)We^{-rt}, \text{ therefore} \\
\dot{I} &= \frac{[f'(I)]^2}{g''(I)f'(I) - g'(I)f''(I)} \left\{ \begin{aligned} &\frac{\phi'(K)}{(1 - \phi(K))} \left[\frac{g'(I)f(I)}{f'(I)} + \Gamma\left(\frac{\gamma}{n}, I, E\right) \right] \\ &+ r \left[\frac{g'(I)}{f'(I)} - \frac{\phi'(K)}{(1 - \phi(K))} W \right] \end{aligned} \right\}. \quad (18)
\end{aligned}$$

It is interesting to note that Kamien and Schwartz's 1978 paper has the R&D effort reach a peak and then decline. The rationale for their result is that they consider an economy in which a stock of capital is used as the only research input and – in combination with the nonrenewable resource – in the production of the composite output which can be either consumed or saved to increase the capital stock. As the nonrenewable resource is depleted, the economy loses its capacity to invest in R&D. In the case examined here, however, the capacity of society to invest in R&D does not decrease with time, and it is socially optimal to increase the amount of resources invested in research for two concurrent reasons: the effectiveness – and the value – of the old technology decreases, while the marginal benefit of investment increases with the capital stock.

Conclusions

We have provided a rationale for the implementation of resistance management plans to prolong the effectiveness of pesticides. However, we have not specified the

mechanisms that might be used. In particular, if there are asymmetries of information on important parameters, solutions in which farmers organize among themselves might be superior to command and control type of measures. Alternatively, if the chemical industry has some degree of market power, it might be best to have the pesticide producers implement resistance management plans. Miranowski and Carlson (1986) give a complete overview of the various possible scenarios.

The model developed above illustrates how there is a trade-off between devoting resources to R&D or to resistance management. The more intensely we use existing pesticides, the more we should invest in the research of backstops. The analysis presented here illustrates how this choice depends on a variety of factors. Specifically, biological parameters such as the characteristics of the pest population, (from mobility to reproduction), the initial frequency of resistance genes and the rate of mutation are crucial elements of the dynamics of resistance development and of the value of susceptibility. Economic and technological parameters determine the level of uncertainty and costs of developing and producing the new technology. Other issues that have not been explicitly addressed are linked to the relative safety attributes of the old and new technologies – which might determine a faster phasing out of old pesticides, for example. Safety elements and the externalities created by pesticides are also linked to consumers' willingness to pay for reduced pesticide use. All these issues are part of the broader determination of the optimal level of pesticide use.

The introduction of new pesticides in the US market has been relatively steady in the last decade (see EPA 1998b, 1998c, 1997, 1996, 1995, 1994). However, this does not necessarily imply that susceptibility to existing pesticides is going to become obsolete.

For example, over 10 percent of the 122 new pesticides registered in the US since 1994 are *Bt* products, either in spray form or plant-pesticides. Moreover, the EPA is in the process of approving or has already approved several new *Bt*-based bioengineered products: nine out of the 12 experimental use permits that the EPA granted in the year 2000 are for *Bt* toxins (EPA 2000). As we noted above, the characteristics of the innovation process matter in determining how much effort to devote to resistance management. If the pesticide industry and the EPA plan on relying heavily on *Bt* products in the future, some kind of resistance management is likely to be needed.

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